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1 Summary

This grant supported experimental research into two aspects of the transition mechanisms on an elliptic cross-section cone, at zero angle of attack. The Purdue Quiet-Flow Mach-4 Ludwig Tube was completed, allowing measurements under low-noise conditions comparable to flight. The boundary layer on the elliptic cone was laminar to the maximum quiet-flow length Reynolds number of 400,000, despite preliminary e^*N transition-estimates suggesting transition at 100,000. Apparatus was developed for generating repeatable perturbations, so that unambiguous and repeatable results can be obtained; this development continues. Repeatable localized perturbations were successfully

generated ahead of the cone, using a pulsed laser. The receptivity and instabilities of a hemispherical nose and a forward-facing cavity were studied by measuring the development of the perturbations as they convect through the shock wave into the body. Measurements of the laser-spot convecting into the elliptic-cone boundary layer are continuing, although preliminary measurements indicate that the growth of the disturbance is small. Controlled localized perturbations are also being generated at the surface of the cone, using a glow-discharge perturber. Preliminary measurements indicate that these perturbations grow into weak wave packets but not turbulent spots. Hot wires, hot-film arrays, and a high-sensitivity differential interferometer are in use and under development for making measurements. Finally, progress was made towards the design and fabrication of a larger Ludwig tube with a higher quiet-flow Reynolds number.

2 Introduction

The results of the work funded under this grant are summarized here; more detail is available in the referenced publications. The work was also supported under AASERT grant F49620-94-1-0326, a gift from the Boeing company, a gift in memory of K.H. Hobbie, a Purdue Research Foundation Fellowship, and NASA Grants NAG-1-1133 (up to 1994) and NAG-1-1607 (up to 1995). Accomplishments and publications are listed with only a minimal effort at apportionment. The work continues under AFOSR Grant F49620-97-1-0037; further publications are expected.

3 Results

3.1 Facility and Elliptic Cone Model

Construction of the Mach-4 Quiet-Flow Ludwig Tube commenced in 1990 with support from NASA Langley (grant NAG-1-1133). The facility was assembled in the summer of 1992 (reference [19]). Quiet flow operation was not demonstrated until the fall of 1993, after the nozzle was polished, with funds from the present grant [20]. Quiet flow was achieved to a length Reynolds number in excess of 400,000 [18], approximately as projected in the proposal. Facility operations improved with time [27, 26]; runs can now be reliably repeated at 30 min intervals. Although a runtime of only 0.12 sec was originally expected, a runtime of 3-4 sec. was actually observed (during this time the pressure slowly drops but the flow remains at Mach 4) [27]. All runs during

the last 3 years have been at total pressures below 2 atm, where the flow in the present nozzle is quiet or near-quiet.

A 4:1 elliptic cone was constructed in late 1994. The cone was designed using the computations of Lyttle and Reed [10, 11] to be as unstable as possible, given the blockage and quiet-Reynolds-number limitations of the tunnel. Later computations by Huang and Herbert suggested that the cone boundary layer would transition to turbulence 1 inch from the nose [4]. However, measurements carried out in 1995 showed that the flow was laminar near the base of the cone (5 inches from the nose) [26]. The supersonic crossflow instability was thus not as strong as expected. Later measurements by Kimmel in AEDC Tunnel B showed that a 2:1 elliptic cone did not transition until a length Reynolds number of 500,000, even in a noisy tunnel [6]. Although this result is good for applications requiring laminar flow, it was a substantial setback to the experimental work, since it made it impossible to study transition under quiet-flow conditions in the present test section.

A substantial portion of Prof. Schneider's effort thus continues to be focused on the design of a higher Reynolds number quiet-flow test section. This work is based on established NASA Langley techniques [23, 24, 25]. Using primarily a gift from the Boeing Company, construction of a larger Ludwig tube has commenced. The area around the test sections of both tubes has been enclosed and air-conditioned, a 3800 cf vacuum tank has been obtained surplus, footings for the tank have been poured, and structure to hold a 30-in. dia. driver tube is being constructed. The design of a long Mach-6 prototype nozzle with an 8-inch diameter exit is nearly complete; quiet flow is projected to a length Reynolds number of about 12 million, about twice that of the Langley Mach-6 nozzle (now boxed). Current plans call for installing this 8-inch prototype in the existing 12-inch Ludwig tube. A 24-inch Mach-6 nozzle would then be built for the new 30-inch Ludwig tube.

To reach Mach 6, where second-mode instability and roughness Reynolds numbers are in the range of Air Force interest, it is necessary to heat the air in the driver tube. Potential for thermal instabilities then exists in the driver tube, and any such buoyancy-driven motions would be convected into the test section and could destroy quiet flow. To address this risk, apparatus for heating the driver tube was installed, and the effect of heating on the quiet-flow Reynolds number was measured. The results show a small adverse effect of running hot gas past a cold nozzle [12]. This is entirely consistent with the observed favorable effect of running cooler gas past a hotter wall [3]. No significant problems with thermal instabilities were observed, although paint dust from the carbon-steel driver tube was a major problem when the driver tube was heated. A stainless-steel driver tube will have to be used for regular

Mach 6 work.

3.2 Instrumentation

3.2.1 Laser Perturber

Receptivity studies require a means of introducing controlled perturbations in the freestream ahead of the model. Since most methods of introducing perturbations also leave a steady wake in the flow, this is difficult at supersonic speeds. Development of a pulsed-laser technique for introducing small localized heated regions commenced in 1992, under Research Initiation grant RI-B-92-03 from the Engineering Foundation/Air Force. Early measurements were carried out with an unseeded Lumonics laser on the benchtop at atmospheric conditions [27]. The hot region was successfully produced, as by earlier workers, but repeatability was poor. Improved optics then allowed generation of the spots under low density conditions similar to those present in the Mach-4 quiet tunnel. Use of a precise injection-seeded laser turned out to be critical to achieving reasonable repeatability [21]. This was serendipitous, for the importance of injection seeding was not foreseen. Indeed, the expensive seeded laser was only procured to allow additional PIV studies, which turned out to be not feasible. Dr. Sakell's encouragement to fund and purchase a single more expensive laser was thus essential to the success of the project.

Generation and measurement of the laser perturbations in the Mach-4 facility involved further development of the optics and improvement of alignment procedures. Repeatability of order 10 percent was successfully demonstrated in early 1996 [15]. Due to motion of the facility and alignment difficulties, the utility of the spot was first demonstrated in blunt-nose flows, rather than for the elliptic cone [8, 26]. This is because it was easier to make the spot convect into a 3/4-inch nose than it was to make it convect into the 0.040-inch nose of the elliptic cone. Robust operation of the laser perturber was not achieved until December 1996, when the apparatus was realigned three times in succession, with a comparable signal achieved on a hot wire in the Mach-4 flow every time.

The results reported in the preliminary exam for John Schmisser's PhD (May 1996) showed that a very weak perturbation could be measured in the elliptic-cone boundary layer with a hot wire, when the laser-perturbation impinged on the nose of the cone. The small uncalibrated signal could only be seen when substantial averaging was used. Now that the perturber is robust, we plan a series of experiments in which the perturber and hot-wire are moved down towards the cone, from well above it. When both the perturber and the

hot wire are positioned in the freestream, the results should be similar to those reported earlier. As the perturber and hot wire are moved towards the cone, it should be possible to measure the processing of the disturbance by the shock in the presence of the wall, and then the receptivity of the boundary layer. When the 4 mm perturbation impinges on the 1 mm nose of the elliptic cone, it spreads out and passes along the cone – it may be that there is a substantial effect of small changes in perturbation position near this location. The results are to be presented in John Schmisser's PhD thesis in August 1997.

3.2.2 Glow-Discharge Perturber

Although the laser-perturber is the only known technique for introducing repeatable perturbations in the freestream of a supersonic flow, it is a difficult and expensive technique with limited flexibility. To complement this technique, a surface glow-discharge perturber is also under development, following Kosinov [7]. Prof. Schneider met with Kosinov at an ITAM meeting in July 1993 and obtained a small flat plate complete with a glow-discharge electrode of the Novosibirsk design. Initial efforts focused on construction of driver electronics similar to those used by the Russians [27]. Later efforts involved complete reconstruction of the electrode and construction of new high-frequency electronics [26]. Ground loops and electromagnetic interference have been the main problems. Recent tests have shown operation of the perturber on the bench up to several MHz. Also, recent experiments in the Mach-4 quiet tunnel seem to show that the perturber can generate small wavepackets when operated in selected frequency bands. Pulsed operation is used, to keep the electrode cool and to allow measurement after the electromagnetic interference from the perturber electronics has ceased [9]. Dale Ladoon's PhD thesis, expected in Dec. 1996, should contain details of the perturber operation, along with the results of the wavepacket measurements on the elliptic cone at Mach 4.

The glow perturber was originally to be used to generate turbulent spots, whose growth and development were to be studied. Although an array of hot-film sensors was successfully developed to perform the measurements (see below), we have not yet been successful in generating turbulent spots in the (unexpectedly stable) elliptic-cone flow. Generation of spots using higher-amplitude perturbations is not being pursued at this time. Development of a higher quiet-Reynolds number test section seems preferable.

3.2.3 Hot Wires and Hot-Film Arrays

Initial measurements were made in the facility with Kulite pressure transducers [18]. Numerous improvements have since been made, in our calibration of both steady and unsteady pressure measurements [14]. These transducers must be used as a standard for the mean pressure during the 3.5 sec. run, since manometers and most pressure transducers are too slow to read correctly. However, the spatial and temporal response of the transducers is limited, and the high-frequency resonance can make signal interpretation difficult.

Hot-wire technique has thus been under development in our lab since 1992. Our wires were fabricated and repaired by George Tennant, using techniques developed at JPL in the 1960's for John Laufer. Much assistance was rendered by Jim Kendall, who was the last JPL worker to use hot wires in supersonic flow [5]. Tungsten wires of diameter 0.00015 inch and length 0.020 inch were initially used. Wire breakage is rare, and nearly always attributable to user error, presumably because of the very low particle content in the filtered air. Constant-temperature technique has been used, due to the ready availability of constant-temperature anemometers. A frequency response of 120 kHz was achieved with the standard bridge on a TSI IFA-100 anemometer with the maximum overheat achievable without oxidizing the wires [26]. The 1:1 bridge on this same anemometer has been used to achieve square-wave frequency responses up to roughly 300kHz.

Calibration efforts began in summer 1996. Nusselt numbers computed for the heat transfer from the wires were a factor of 2 above accepted empirical values, and accepted correlations for the heat-loss to the needle supports agreed in showing unacceptably large end effects. Use of 0.0001-inch Pt-Rh wires then commenced. No problems with wire breakage were experienced. Initial calibrations of Nusselt number agreed well with accepted values, and these wires also permit the use of higher temperatures, higher overheats, and thus greater sensitivity to small fluctuations. Although Mr. Tennant recently retired from part-time hot-wire work, we hope to have calibrated hot-wire measurements with the new wires within a few months.

Hot-film arrays have been used in low-speed flows for measurement of laminar-turbulent intermittency and transition, for some time [17]. Exploratory measurements were performed in a window blank on the wall of the Mach-4 quiet tunnel during 1995; these showed that the sensors would also work at high speed (somewhat to the surprise of the first author) [16]. Although the sensors cannot resolve the high-frequency fluctuations in the turbulent spots, they are capable of detecting the presence of spots as a function of time. The signal is very weak, and the noise from the commercial anemometer is too

large to make good measurements of intermittency. Four channels of home-built constant-temperature anemometry were fabricated for the work reported in reference [16]. Unfortunately, the AC-coupled response of these anemometers did not allow use of the more reliable PDF method for computing intermittency [17]. Ten channels of DC-coupled anemometers were thus built during summer 1996. Although preliminary tests suggest these will work well, definitive studies have not yet been performed (see also [26]).

3.2.4 Differential Interferometer Development

A high-sensitivity differential interferometer is also being developed, following Smeets, for measurements of optical path length to a noise limit of 10 millionths of a wavelength [26]. Preliminary measurements in the Mach-4 flow indicate the single-point device works well, as long as the boundary layer on the nozzle wall is laminar. The noise from a turbulent boundary layer on the nozzle wall is presently comparable to the signal expected from the boundary layer of the model. The device is to be tested in detail using the hemispherical-nose flow and the laser perturber. Methods of reducing the sensitivity in the region of the nozzle-wall boundary layer are also being investigated. This device is nearly the only advanced optical method capable of measuring the very small fluctuations present in unstable laminar flows [2].

3.3 Results for Instability and Transition

At the beginning of this effort, it was thought that the crossflow instability present on the elliptic cone would be so strong that transition would be caused at very low Reynolds number. As discussed above, it was shown that the elliptic cone was laminar to Reynolds numbers 5 times higher than those predicted from nonparallel e^N computations for a sharp cone [26]. This relatively weak instability has made useful measurements on the elliptic cone more difficult. To date, most of our successful measurements have been in 'easier' flows that have served as stepping stones for developing the instrumentation.

Receptivity measurements have been made in the subsonic region of a hemispherical nose [13]. This work was primarily supported by NASA Grant NAG-1-1607 and by a fellowship from Purdue's NASA Space Grant program. When the laser perturbation convects into the subsonic region near the nose, the pressure at the stagnation region rings and decays [26]. This ringing is potentially very significant, for it suggests that broadband high-frequency fluctuations and particle impacts are converted into fluctuations in a specific frequency band, by the receptivity of the nose. If the nose-region ringing is in a frequency band

that generates substantial instability waves downstream, nose-region ringing could be a significant part of the overall transition process. Nose-region ringing could be a partial explanation for the blunt-body paradox. However, ringing of the Kulite pressure transducers also occurs, and makes unambiguous assessment of the nose-region ringing difficult. Similar ringing *has* been observed with two different blunt-nose shapes [8]. However, definite results await experiments with a different sensor such as a hot wire on the shoulder of the hemisphere, or the differential interferometer.

Receptivity experiments have also been performed for a forward-facing cavity, as a simple demonstration of the utility of the laser perturber. The large fluctuations observed in conventional wind tunnels (roughly 5%) nearly disappear when measurements are made under quiet conditions comparable to flight (fluctuations roughly 0.05%). The fluctuations in the cavity are *not* due to absolute instabilities that develop regardless of the incoming freestream; rather, they are amplified from the incoming freestream noise. This was clearly demonstrated by convecting the laser perturbations into the cavity. Clean decaying oscillations were observed [8], and the decay rate was quantified as a function of cavity depth. The utility of the forward-facing cavity flow should be completely reassessed in view of these first quiet-tunnel results.

Computations of the crossflow instability on the sidewalls of square wind-tunnel nozzles have also been completed and published [1]. This work was funded by NASA Grants NAG-1-1607 and NAG-1-1133. This work, and related measurements, shows that axisymmetric nozzles are the most likely candidates for high Reynolds number quiet flow wind tunnels [24, 23].

Finally, reviews have been prepared of the hypersonic transition literature, particularly as it relates to tunnel noise effects and flight extrapolation. These have been presented to the Space Shuttle program [22], and will be presented at the AGARD meeting on Sustained Hypersonic Flight in Paris in April 1997.

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